Well-Field Design Criteria for Coastal Seawater Development

WELL-FIELD DESIGN CRITERIA FOR COASTAL SEAWATER DEVELOPMENT

by

Barney P. Popkin
Environmental Research Laboratory
Tucson International Airport
Tucson, Arizona 85706

ABSTRACT

The University of Arizona's Environmental Research Laboratory, with the Universidad de Sonora, has operated a research station at Puerto Peñasco on the northeastern Gulf of California, Sonora, Mexico, since 1962. Research projects have included solar distillation, greenhouse agriculture, shrimp aquaculture, and halophyte irrigation. These require a dependable supply of filtered, temperate seawater. Proposed aquacultural expansion requires a large water supply. The thin, coastal, water-table coquinoid-beachrock aquifer has a high permeability, contains seawater and could sustain high yielding wells from a limited area. Well performance indicators (yield, specific capacity, efficiency and losses) are influenced by design, drilling, development and siting, and aquifer properties and hydrogeologic boundaries. Design should include full aquifer penetration, open-area screens, sized gravel pack and proper pump submergence. Drilling should be by mudless reverse circulation. Development should consist of simultaneous air lifting and jetting. Siting should include proximity to the recharging Gulf and adequate well spacing. Total well-field production is controlled by individual and collective well performance, and by regional hydrogeologic conditions.

INTRODUCTION

The University of Arizona's Environmental Research Laboratory (ERLAB), with Universidad de Sonora, has operated a research station (U.E.P., Unidad Experimental Peñasco) at Puerto Peñasco on the northeastern Gulf of California, Sonora, Mexico, since 1962 (Figure 1). Research projects have included solar distillation of seawater, greenhouse vegetable agriculture, controlled-environment shrimp aquaculture, and halophyte irrigation. These require a dependable supply of filtered, temperate seawater.

In 1978, a one-acre prototype shrimp farm was built. The facility's success has encouraged proposed aquacultural expansion, which requires a large water supply. Various water-supply studies have sought to describe the local hydrogeology, assess the feasibility of expansion, and evaluate aquifer and well performance (Riley and Percious, 1974; Percious, 1976; Water-Supply Study Team, 1979; Popkin, 1979, 1980; and DeCook and others, 1980).

This paper summarizes current thinking on well-field design criteria for groundwater development of coastal seawater at Puerto Peñasco. This thinking is based on a combination of hydrogeologic theory, engineering and field experience, professional and trade literature, consultation, and water-well and pump institutes.

WATER WELLS

Water wells are constructions which allow the development of a groundwater source. They are commonly vertical. Wells usually consist of a casing and screen, possibly a gravel pack, and a pump.

Water-well performance includes factors, indicators, improvements, and effects.

WELL-PERFORMANCE FACTORS

Well-performance factors include design, drilling, development, siting, and aquifer properties and hydrogeologic boundaries. Wells should be completed and maintained to take best advantage of the hydrogeologic environment to achieve best well performance.

WELL-PERFORMANCE INDICATORS

Well-performance indicators include well yield, drawdown, specific capacity, well and aquifer losses, and well efficiency. Best performing wells will have high yield, capacity and efficiency, with relatively low drawdown and well losses.

Indicators for future good-performing, coastal seawater wells in Peñasco are anticipated to have a well yield of 1,500 to 2,000 gpm, drawdown of 25 to 30 ft, specific capacity of 50 to 70 gpm/ft, well losses of five to ten ft, and well efficiency of 40 to 50 percent. Current wells show well yields of 250 to 1,000 gpm, drawdowns of 20 to 40 ft, specific capacities of 11 to 54 gpm/ft, well losses greater than 10 ft, and efficiencies of less than 25 percent for the eight existing production or production-test wells in the coquina.

Once the aquifer properties are estimated from pumping tests, some useful equations for well-performance indicators are:

$$SC = (T \times E) / (1440 \times 100), \qquad (1)$$

$$Y = SC \times D, \quad \text{(Todd, 1964)} \qquad (2)$$

$$D = B\,Q + C\,Q^n, \quad \text{(Todd, 1964)} \qquad (3)$$

$$E = (100 \times B\,Q) / D, \qquad (4)$$

where SC is specific capacity (gpm/ft), T is aquifer transmissivity (gpd/ft), E is well efficiency (percent), Y is well yield (gpm), D is drawdown (ft), B Q is aquifer loss (ft) and $C\,Q^n$ is well loss (ft), Q is well discharge (cfs), and n is generally 2.00. B is the aquifer loss constant (sec/ft^2) and is equal to $\ln (r_o/r_w) / 2\pi Pb$, where r_o and r_w are radii of influence and well (including gravel pack) respectively, P is aquifer hydraulic conductivity (ft/sec), and b is saturated aquifer thickness (ft). C is the well loss constant (sec^2 /ft^5). Related methods of estimating efficiency and well losses include time-drawdown analysis of multiply space observation wells (Johnson, 1975) and step-drawdown or production tests (Walton, 1970). Well efficiencies of the best, newly drilled wells are probably no better than 70 percent.

WELL-PERFORMANCE IMPROVEMENTS

Improvements in existing wells may include simultaneous pumping and jetting for redevelopment, bailing for well cleaning, removing screen encrustation by acidizing or low-explosive blasting, well deepening to screen more of the aquifer, lowering pump bowls to increase pump submergence and reduce cavitation, shrouding pump impellars against screened zones to better distribute entrance velocity and provide pump cooling, redesigning pumps for higher efficiency, installing recharge sources in the zone of influence, and sealing aerated screens and/or using floating baffles to reduce cavitation.

Improvements in planned wells include use of best design, drilling, development, and siting. Well design should include strong and stable well materials, full aquifer penetration, open-area screens, sized gravel pack, and proper pump submergence. Well drilling should be by mudless reverse circulation, with nearby supply-observation well or wells for proper aquifer tests. Aquifers may be stimulated with acid, hydraulic pressure, or blasting, in some cases, to decrease flow resistance near a well. Well development should consist of simultaneous air lifting and jetting to remove fines and settle gravel pack. Well siting should include proximity to recharge source, and adequate well spacing to minimize well interference.

Existing seawater production wells in Peñasco use: slotted fiberglass, asbestos cement, or polyvinyl chloride casing (six-percent open area); some slotted sections above the pumping water level; coarse, angular and unsorted gravel; and inadequately submerged pump bowls. They were drilled initially by direct rotary, and later by reverse circulation. Development was by air lifting and overpumping. Observation wells were not installed with the initial direct rotary wells, though they were completed with reverse circulation wells. Proximity to the recharging Gulf and well spacing are adequate. Asbestos cement casing unfortunately has a tendency to separate.

Future wells (Figure 2) should screen the lower 5/6ths of the coquinoid aquifer with at least 16-in. diameter, fairly open (>50%), wire-wrapped #316 stainless steel, use round and smooth 1/8 to 1/4 inch gravel for three-inch gravel pack, and have a pump sump. Mudless reverse-rotary drilling, and simultaneous air lifting and jetting well development should be used. Careful siting to recharge source and for well spacing should be reviewed.

WELL-PERFORMANCE EFFECTS

Well-performance effects include cost, energy, engineering, supply and quality considerations. Poorly performing wells have lower yields, higher drawdowns, lower specific capacities, higher well losses, and lower efficiencies. They increase pumping costs, require more wells, pumps and controls for the same total design yield, and need more frequent maintenance and replacement. They lead to overestimation of aquifer storage, and underestimation of aquifer transmissivity and hydraulic conductivity, which leads to underestmating well-field potential, and available groundwater, and overestimating arrival time of contaminants. Poorly performing wells increase sand pumping, gravel pack instability, screen corrosion, and localized subsidence, and decrease well life. Wells sited too far inland may induce flow of highly saline groundwater.

WATER-WELL FIELDS

Well fields are composed of two or more production wells. Properly designed fields should maximize water production, minimize production costs, and provide an adequate and potential water supply for the project life.

TRANSIENT CONDITIONS

Short-term well-field operation may only respond to transient conditions, until equilibrium or steady state is reached. Equilibrium occurs when drawdown becomes constant. Well interference, and hydrogeologic barriers are particularly important during transient conditions.

Aquifer transmissivity and storativity, anticipated well yield, and Theim and Theis type analyses are used to space wells to minimize well interference (Todd, 1960, 1964; Viessman and others, 1977). The total drawdown at a well in a field is the sum of drawdowns induced by interfering well yields. A hydrogeologic barrier or recharge boundary can be mathematically analyzed as an image source or sink (Jacob, 1950; Wisler and Brater, 1959; Todd, 1960, 1964; DeWiest, 1965; Viessman and others, 1977).

EQUILIBRIUM CONDITIONS

When steady state is reached, anticipated well yield and drawdown, and aquifer hydraulic conductivity, saturated aquifer thickness, and recharge boundary are the controlling factors of well-field performance for a linear well field paralleling the Gulf coast. Since the recharging Gulf acts as the steady-state water source to nearby wells, well and field yields are dependent on the distance of the field to the recharge boundary, the length of the boundary through which recharge water flows to each well, and hydraulic properties of the aquifer.

A LINEAR COASTAL WELL FIELD

A linear coastal well field may be designed from steady-state considerations. The following analysis can be applied to a continuous or segmented well field. If the anticipated yield of each well is Q_w (gpm), based on well-performance characteristics, the recharge border yield to each well is Q_b (gpm), and convergence loss factor of (1-f) occurs, then the following equation relates border yield to well yield.

$$Q_w = f\ Q_b. \qquad (5)$$

Values of f likely range from 0.50 to 0.70 (see Appendix).

The recharge border yield is derived from the continuity equation of discharge equals velocity times cross-sectional area, or

$$Q_b = c\ V\ A = c\ K\ I\ A = c\ K\ D\ R\ B\ /\ G, \qquad (6)$$

where Q_b is recharge border yield (gpm), V is groundwater flow velocity (ft/day), A is cross-sectional area of flow (ft^2), K is aquifer hydraulic conductivity (ft/day), I is groundwater hydraulic gradient, D is drawdown in the pumping well (ft), G is inland distance of the well field from the Gulf recharge boundary (ft), R is distance between production wells (ft), and B is saturated aquifer thickness (ft). The c is a unit conversion factor, equal to 7.48 gal/ft^3/1,440 (min/day), or 5.19×10^{-3}.

This analysis assumes that the static groundwater level is approximately equivalent to sea level, so that drawdown D represents the change in hydraulic head from the recharge boundary to the pumping well.

Substituting equation 6 in equation 5, and rearranging terms, we can calculate the maximum allowable distance between wells, R, by

$$R = G\ Q_w /\ c\ f\ K\ D\ B, \qquad (7)$$

and for the maximum allowable distance between the well field and the Gulf recharge boundary, G, by

$$G = c\ f\ K\ D\ B\ R\ /\ Q_w. \qquad (8)$$

The calculation is made by first estimating R or G (see Appendix). If the length of available land paralleling the recharging Gulf is L (ft), the number of possible wells, N, from this analysis is

$$N = L\ /\ R, \qquad (9)$$

where N is rounded off to the lower integer.

The total water yield from the production field, Q_t (gpm), is

$$Q_t = N\ Q_w. \qquad (10)$$

If the aquacultural water-use rate is Q_u (gpm/ac), then the total design aquacultural acreage or farm size, F (ac), is

$$F = Q_t\ /\ Q_u, \qquad (11)$$

where F is rounded off to the lower integer.

PROJECTED WELL FIELD

Two linear coastal well fields are hypothetically projected in the coquinoid aquifer paralleling the coast, based on the above analysis. If all the coastal land from Cerro Peñasco to the Estero Marua (Figure 1) is available for a well field, 60 wells could provide enough water for about 90 acres of shrimp aquaculture. If the coastal land from the U.E.P. to the Las Conchas Park is available, 20 wells could provide enough water for about 30 acres of shrimp aquaculture.

CONCLUSIONS AND COMMENTS

Total well-field production is controlled by individual and collective well performance, and by regional hydrogeologic conditions. Proper design, drilling, development and siting of a linear well field, paralleling the Gulf coast of Puerto Peñasco must take advantage of the recharging Gulf. Such a well field can provide large, dependable amounts of filtered, temperate seawater for controlled-environment shrimp aquaculture.

Complete well-field analysis should include evaluation of aquifer, well, field, pump, hydraulic, energy, and water-use components. Though economics, land-use impacts, and pipeline engineering are not reviewed here, the operation of a large-scale coastal seawater well field for aquaculture appears

feasible in Peñasco.

Well testing, maintenance, treatment and pump selection are not discussed here, as there is abundant literature (See References). Wells require proper and periodic testing to evaluate performance, maintenance to continue best operation, and treatment to correct declining production.

ACKNOWLEDGEMENTS

I thank P. Brenneman (Arizona Maintenance), R.P. Chagnon (Johnson Screens), D. Crowe (ECASA), R.W. Curry (Gilbert Pump), K.J. DeCook, D.J. Percious and E.S. Simpson (University of Arizona), and W.C. Walton (Camp Dresser & McKee) for their technical advice on well and field design. I also thank the University of Wisconsin-Extension (1979) and the Irrigation Association (1980) for their Water Well Institute and Short Course on Pumps and Pump Controls, respectively. I thank Peggy Stowe for her help in the preparation of this manuscript, and Julie Jones and Vicki Schale for their help in slide preparation.

Funding for this research was provided by the Coca-Cola Company and F.H. Prince and Company, Inc. as part of their continuing interest in controlled-environment shrimp aquaculture.

REFERENCES CITED

American Society of Civil Engineers. 1961. Ground water basin management. ASCE-Manual of Engineering Practice No. 40, N.Y.

American Water Works Association. 1973. Ground water. AWWA Manual M21, N.Y.

American Water Works Association. 1977. Vertical Turbine Pumps-Line Shaft and Submersible Types: ANSI/AWWA E101-77, Denver, Colo.

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill, N.Y.

Colt, Ind. 1979. Hydraulic Handbook. Kansas City, Kan.

DeCook, K.J., S. Ince, B.P. Popkin, J.F. Schreiber, Jr., and J.S. Sumner. 1980. Exploration for saltwater supply for shrimp aquaculture, Puerto Peñasco, Sonora, Mexico. Hydrology and Water Resources of Arizona and the Southwest, Vol. 10.

DeWiest, R.J.M. 1965. Geohydrology. Wiley, N.Y.

Irrigation Association. January 1980. Notebook on Short Course on Pumps and Pump Controls. Silver Spring, MD.

Jacob, C.E. 1950. Flow of ground water. In Hunter Rouse, ed. Engineering Hydraulics. Wiley, N.Y.

Johnson Division. 1975. Ground Water and Wells. UOP, St. Paul, Minn., 4th print.

Karassik, I.J. and R. Carter. 1960. Centrifugal Pumps: Selection, Operation and Maintenance. McGraw-Hill, N.Y.

Percious, D. April 1976. Prototype Seawater Well for Unidad Experimental Peñasco Aquaculture Facility and Related Hydrological Considerations. ERLAB, Univ. of Ariz., Tucson, Ariz.

Popkin, B.P. November 1979. Results of Production-Test Well Drilling Program at Puerto Peñasco, Sonora, Mexico. ERLAB, Univ. of Ariz., Tucson, Ariz.

Popkin, B.P. February 1980. Engineering Analysis of Production-Test Well Drilling Program, Puerto Peñasco, Sonora, Mexico. ERLAB, Univ. of Ariz., Tucson, Ariz.

Riley, J. and D. Percious. June 1974. Puerto Peñasco Hydrology and Well Development. ERLAB, Univ. of Ariz., Tucson, Ariz.

Scott, V.H. and J.C Scalmanini. 1978. Water wells and pumps: their design, construction, operation, and maintenance. Univ. of Calif. Div. Agri. Sci. Bull. 1889, Davis, Calif.

Todd, D.K. 1960. Ground Water Hydrology. Wiley, N.Y.

Todd, D.K. 1964. Groundwater. In Ven Te Chow, ed. Handbook of Applied Hydrology. McGraw-Hill N.Y.

United States Environmental Protection Agency. 1975. Manual of Water Well Construction Practices. EPA - 570/9-75-001, Washington.

University of Wisconsin-Extension. November 1979. Notebook for the 5th National Water Well Institute. Madison, Wis.

Viessman, W., Jr., J.W. Knapp, G.L. Lewis, and T.E. Harbaugh. 1977. Introduction to Hydrology. Dun-Donnelley, N.Y., 2nd ed.

Walton, W.C. 1962. Selected analytical methods for well and aquifer evaluation. Illinois State Water Surv. Bull. 49.

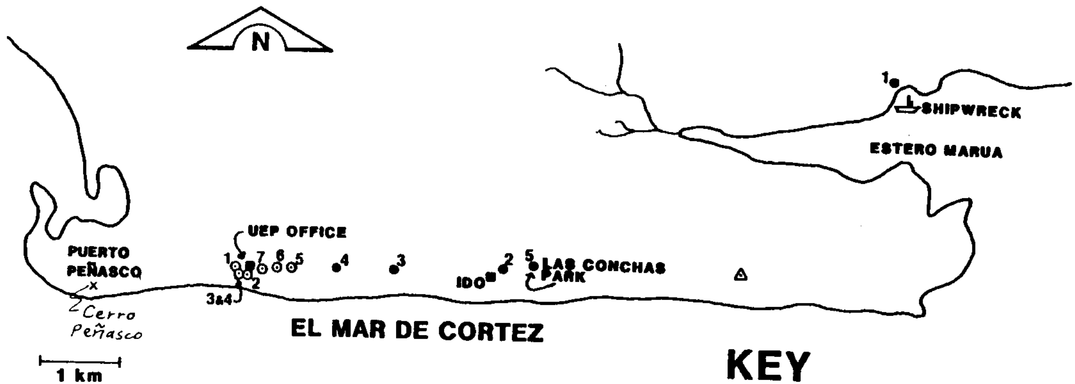
Walton, W.C. 1970. Groundwater Resource Evaluation. McGraw-Hill, N.Y.

Water-Supply Study Team. May 1979. Water-Supply Feasibility for Ten-Hectare Shrimp Aquaculture Facility at Puerto Peñasco, Sonora, Mexico. Report to ERLAB from the Water Resources Research Center, Univ. of Ariz., Tucson, Ariz., 3 vols.

Wisler, C.C. and E.F. Brater. 1959. Hydrology. Wiley, N.Y.

APPENDIX

It is useful to make a plot of inland distance of a linear well from the Gulf recharge boundary (G), versus steady state well drawdown due to well interference and Gulf recharge for a family of wells a given distance apart (R). Such a plot is made using aquifer properties of transmissivity and storativity, long-term pumping time (ten years), well yield, and the Theis equations applied to discharge wells and recharge images. From this plot, it is possible to select a suitable combination of R and G to give acceptable interference drawdown (see equations 7 and 8). It appears that an R of about 500 ft, and a G of about 300 ft is the optimal siting, given a transmisssivity of about 200,000 gpd/ft and a storativity of about 0.25. This is equivalent to an f value in the range of 0.50 to 0.70 (See equation 5), where f reflects convergence losses from a recharge border to a well, or the cumulative drawdown impact from interfering wells and recharge images.



KEY
- SITE NUMBER
- ERL WELL NUMBER
- ABANDONED LAS CONCHAS WELL-16"

LOCATION OF TEST SITES

PRODUCTION-Test well drilling program
Puerto Peñasco, Sonora, Mexico

Figure 1.

Figure 2.

Sketch of Proposed Well Design